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X-ray Cluster Large Scale Structure and Cosmology

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Abstract. We outline main arguments in favor of cosmological X-ray surveys of galaxy clusters. We summarize recent advances in our understanding of cluster physics. After a short review of past surveys, we present the scientific motivations of the XMM Large Scale Structure survey. We further illustrate how such a survey can help constrain the nature of the dark energy as well as cluster scaling law evolution, i.e. non gravitational physics.

1. Introduction

Clusters of galaxies occupy a strategic position in the multi-parameter cosmological space:
- They constitute the most massive entities having reach some equilibrium state in the universe. Masses range from a few 10^{13} $M_\odot$ for groups up to a few 10^{15} $M_\odot$ for rich Coma-type clusters;
- They are located at the nodes of the cosmic network.
- Maps of the distribution of clusters trace the matter distribution over large volumes;
- Clusters grow from accretion at a rate that depends on the embedding cosmology;
- As "relaxed" objects, they can be considered to have decoupled from the general expansion;
- In the cluster total mass budget, galaxies account for only 5%, intra-cluster gas for 15%, the rest of the mass being in the form of dark matter;
- "Equilibrium" is twofold: virial equilibrium for the galaxies and hydrostatical equilibrium for the gas within the cluster potential;

This short list provides compelling arguments for using clusters as cosmological probes rather than galaxies being complex, highly non-linear objects. We should, however, underline that the physics of clusters, as revealed by the two last generations of X-ray observatories (*ROSAT* and *ASCA* then *XMM* and *Chandra*), is not as simple as suggested by the above picture: phenomena other than gravity also impact on cluster properties. They are mostly triggered by interactions involving gas and (active) galaxies within the dark matter potential. Among the currently investigated questions, we may cite:
- Cluster relaxation processes and time scales after merger events, i.e. resorption of clumps. Observables involved are: galaxy velocity and space distribution; gas density and temperature maps; radio halos.

- Modelling gas cooling and understanding the cooling flow problematic. This involves extensive numerical simulations as well as high resolution X-ray spectroscopy;
- The presence of magnetic fields and of a potentially non negligible contribution from high velocity electrons (cosmic rays) in the total cluster energetic budget;
- The impact of stellar activity (supernovae) in cluster galaxies to the heating and enrichment of the cluster gas;
- The role of gas stripping and accretion in the evolution of cluster galaxies;
- The role of cluster AGN in the energetic budget and magnetic field properties. This is especially relevant for cooling flow studies;

A review of these aspects can be found in Mushotzky (2004, this volume).

2. Why X-ray cluster surveys?

Because of the many links with fundamental physics, X-ray cluster data offer significant advantages over optically-selected cluster samples.
In absence of extra heating (other than shocks) and cooling mechanisms, the gas trapped in the cluster gravitational potential is heated up to the virial temperature:

$$kT \sim 6.7\ (\frac{M_{200}}{10^{15} M_{\odot} h^{-1}})^{2/3} \quad keV$$

where M_{200} is the mass enclosed within the virial radius[1]. From this, it occurs that cluster temperatures approximatively range from 1 to 10 keV which correspond to wavelengths of the order of 10-1 Å, i.e. to the X-ray domain. The density of the intra-cluster medium is of the order of one atom per liter, its metallicity about 0.3 solar, most of the gas being totaly ionized, except for some heavy elements like iron. The X-ray emission from such an optically thin plasma can be described by a bremsstrahlung continuum emission, plus possible fluorescence lines from heavy elements. The emissivity is thus simply proportional to the square of the electron density.
From this, one expects simple scaling relations connecting cluster X-ray luminosities to temperatures and, further, to cluster masses (the only parameter that enter any cosmological consideration). Observations do indeed show strong correlations between $L-T-M$, but with a relatively large scatter. Although the dispersion can be ascribed, for a large part, to the individual cluster formation and relaxation histories, the relations provide useful tools to link observations to theory in statistical analyses. Moreover, the fact that the slopes of these relations were found to be somewhat steeper than that predicted from simple scaling laws implied by the virial equilibrium, pointed toward additional heating (or cooling) mechanisms, other than purely gravitational. Main mechanisms usually invoked are mentioned in the previous section and their relative efficiency is investigated by means of hydrodynamical simulations.

[1] The virial radius is usually defined as cluster-centric radial distance where the dark matter density is 200 times higher than that of the mean critical density considered at the cluster's redshift

From the observational point of view, the presence of extended X-ray emission at high galactic latitude almost unambiguously points toward a deep cluster potential well. Moreover, projection effects are much less of a concern than in the optical. At moderate sensitivity ($\sim 10^{-14}$ erg/s/cm^2 in the [0.5-2] keV band, which is obtained in a few ks with *XMM*), the X-ray sky is "clean". With a source density of about 200 deg^{-2}, clusters represent some 15% of the population, the rest being mostly point-like active galactic nuclei. For comparison, an extragalactic field (so-called "empty field") observed in the I optical band in one hour with a 4m-class telescope reveals a faint galaxy density of the order of 10^5 deg^{-2}. Sophisticated multiresolution wavelet-based algorithms, now offer reliable means to flag the presence of faint extended sources down to the (Poissonian) limit of the X-ray photon signal. This renders the detection of X-ray clusters substantially more direct and more quantitative than in the optical. Selection effects can be modelled by means of extensive simulations (Valtchanov et al, 2001).
Finally, because clusters are among the intrinsically brightest X-ray sources, the X-ray domain is a priori ideally suited to investigate the distant universe that is, well beyond $z = 1$.

3. Cluster surveys prior to XMM

HEAO-1 (1977) was the first mission to provide an X-ray all-sky survey enabling cluster statistical studies. Some 100 nearby clusters were inventoried. First determination of the cluster X-ray luminosity function and a qualitative study of the sky distribution of X-ray clusters, as well as correlations between L_X and optical richness were attempted (Piccinotti et al, 1982 and Johnson et al, 1983).
With the advent of X-ray imaging with focussing optics in the 80s, particularly with *Einstein*, a new era was opened in X-ray cluster surveys. The *Einstein* Medium Sensitivity Survey provided a sample of 93 clusters out to a redshift of 0.58 and a flux limit of $S_{[0.3-3.5]\ keV} = 1.33\ 10^{-13}$. These "serendipitous" sources were found in the field of unconnected pointed observations covering a total of 780 deg^2 (Henry et al, 1992) and provided first hints about X-ray cluster evolution.
In 1990, the *ROSAT* All-Sky Survey (RASS) was the first X-ray imaging mission to undertake the coverage of the entire sky (Voges et al, 1999). With average sensitivities of the order of 2-20 10^{-14} erg cm^{-2} s^{-1} in the [0.1-2.4] keV band, (FWHM $\sim 100''$) and the low instrumental background of the PSPC detector, the RASS laid the basis for numerous unprecedented statistical studies. After years of intensive follow-up campaigns, more than 1000 RASS clusters out to a redshift of ~ 0.5 were inventoried. (1) Samples covering a contiguous area, thus suitable for large scale structure studies. REFLEX for the southern hemisphere with 450 objects ($z \leq 0.3$) it is the largest homogeneous compilation to date, down to a flux limit of 3 10^{-12} erg cm^{-2} s^{-1} in [0.2-2.4] keV (Böhringer et al, 2001); NORA for the Northern hemisphere (Böhringer et al, 2002), and the North Ecliptic Pole survey involving the 80 deg^2 deepest region of the RASS provided 64 clusters out to $z \sim 0.81$ (Henry et al, 2001). (2) Samples gathering well defined classes of clusters such as the Massive Cluster Survey (Ebeling et 2001) with the goal of detecting the most massive clusters down to the RASS

sensitivity limit.

After the completion of the RASS, *ROSAT* was run like an ordinary observatory, performing thousands of deep targeted guest observations. Many of these pointings were suited to the search for serendipitous clusters, following onto the EMSS heritage. Numerous studies led to the detection of several hundreds of clusters out to a redshift to unity or above. The large majority of the serendipitous data indicate a mild cluster evolution of cluster properties, compatible with a ΛCDM-type cosmology. A summary of the survey work and associated cosmological constraints can be found in Rosati et al, (2002). We describe below in more detail the impact of LSS studies.

4. Constraining cosmology

In the current quest for the cosmological parameters, clusters studies, beside CMB and supernova studies, provide critical independent constraints as they do not rely on the same physical phenomena. It is also necessary, as a consistency check, to compare constraints obtained separately from the high and low redshift universes. Like for galaxies, topological investigations may involve tools as simple as the 2-point correlation function, percolation analysis or more refined ones like Minkowski functionals or the genus approach (e.g. Kerscher et al, 1997) necessitating, however, rather high-level statistics. The cluster correlation function which is proportional to the Fourier transform of $P(k)$, the power spectrum of density fluctuations, is quite sensitive to the spectrum shape (Γ). The amplitude of $P(k)$ is strongly constrained by the cluster number density and usually expressed in terms of σ_8, the r.m.s density fluctuations within a top hat sphere of 8 h^{-1} Mpc radius (the local determination of cluster abundance, however, only enables the determination some combination of $\sigma_8 \Omega_m^\alpha$). It is thus especially relevant to combine both quantities in order to tighten the possible parameter space (e.g. Moscardini et al, 2001). A didactic illustration of such a procedure can be found in Schuecker et al, (2003) for the REFLEX sample.
As for any survey, constraining cosmological parameters requires proper modelling of the selection effects, which is best achieved with simulations. In the case of X-ray cluster surveys, special attention must be paid to sensitivity variations across the survey area and to the fact that some clusters may remain undetected (e.g. low surface brightness objects, but not necessarily low-mass entities). Further sources of uncertainty such as the intrinsic scatter present in the $L_X - M$ relation must be integrated into the final calculations. For high-z redshift samples, evolutionary considerations as to cluster scaling laws have also to be taken into account.

5. The XMM Large Scale Structure Survey

Tracking back evolution in cluster properties largely improves constraints on cosmological parameters, to which clusters are especially sensitive like the matter density of the universe and also, in some respect, the nature of the dark energy

(see below). In particular, it allows breaking the $\sigma_8\Omega_m^\alpha$ degeneracy (Bahcall et al, 1997).
Launched in 1999, the XMM observatory offers unrivalled collecting area together with good imaging capabilities and a large field of view. This translates into the following numbers: a PSF of $6''$, which enables flagging clusters as extended sources out to a redshift of 2, if any; a sensitivity reaching 5 10^{-15} erg cm^{-2} s^{-1} in the [0.5-2] keV band for a 10 ks exposures and a field of view of $30'$. Although not initially conceived as a survey instrument, its properties make of XMM an ideal cluster finder. Taking advantage of this unique opportunity, we have undertaken an extragalactic medium deep survey, the XMM Large Scale Structure survey (XMM-LSS), with the goal of investigating for the first time evolutionary trends in the space distribution of clusters out to a redshift of unity. Requiring an accuracy for the cosmological parameters comparable to that achieved by the REFLEX low-z sample, implies obtaining some 2×400 clusters in the $0 < z < 0.5$ and $0.5 < z < 1$ redshift bins. This can be obtained from a 8×8 deg^2 area paved with 10 ks XMM pointings (assuming a ΛCDM universe). Such a geometry also ensures probing characteristic scales significantly larger than $100h^{-1}$ at $z = 1$. The X-ray survey with its associated multi-wavelength programmes are described in detail by Pierre et al, (2003). We summarize below main expected cosmological implications, especially in the context of the recent WMAP results.

6. Cosmological implications of the XMM-LSS

Prospects that the final XMM-LSS catalogue will offer for measuring cosmological parameters have been studied in detail by Refregier et al, (2002) for a ΛCDM model. Cluster abundance data provide strong constraints on the Ω_m–σ_8 combination. Adding information from the correlation function restrains the allowed region of the $\Omega_m - \Gamma$ plane to a narrow range. Given the survey design, the *simultaneous* expected precision on Ω_m, σ_8 and Γ is about 15%, 10%, 35% respectively.
It is well known that compared to $\Omega_m = 1$ models, open universes show a much less rapid evolution of the cluster number density (see Refregier et al, 2002, for comparative $n(z)$ for the XMM-LSS). We further show on Fig. 1 the predicted X-ray cluster redshift distribution for two flavours of the dark energy. X-ray counts appear to be sensitive to the nature of the dark energy and to be more sensitive for detecting clusters above $z > 0.3$ than ground-based weak lensing. In addition, thanks to the large area surveyed, it will be possible to constrain the population of X-ray bright (massive?) clusters above $z > 1$. For a ΛCDM cosmology, the probability of finding a Coma-type cluster (8 keV) between $1.5 < z < 2$ over the entire survey area of 64 deg^2 is of the order of 0.001, compared to 0.3 in the $0.5 < z < 1$ range; getting a few such high-z clusters, would thus be most interesting!

Given the fact that we are now entering a high-precision cosmology era with CMB and space supernovae experiments, we may address the question of cluster evolution from a different point of view. Assuming that the cosmological parameters are known, a cluster survey can be used to constrain the evolution-

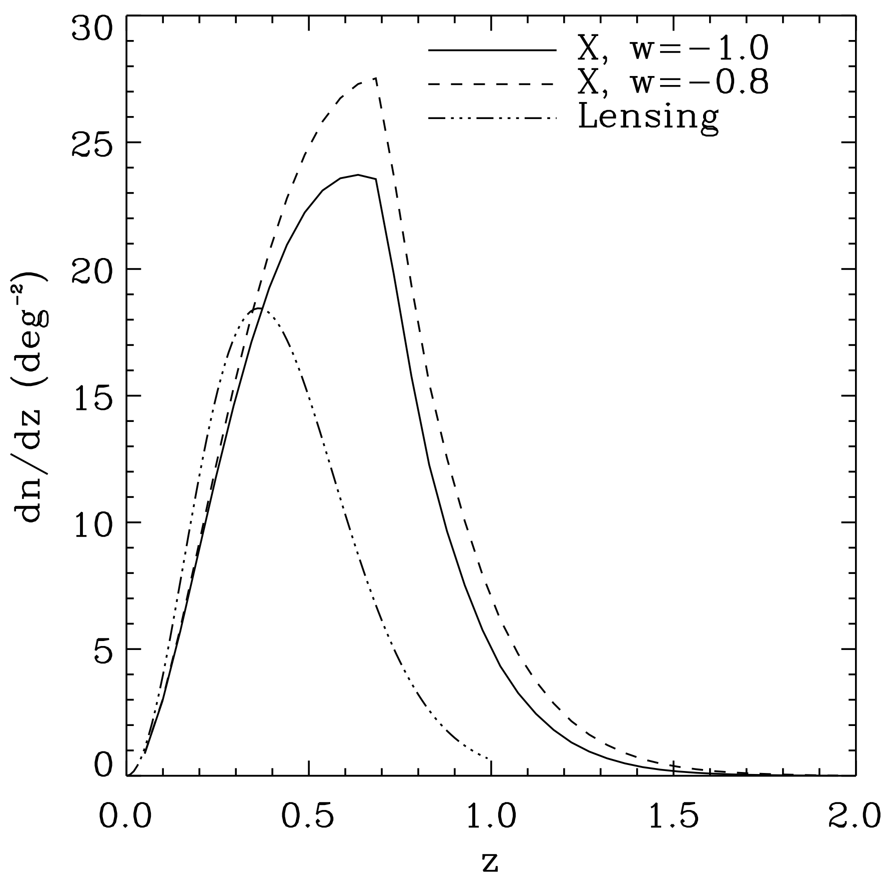

Figure 1. Predicted redshift distribution, dn/dz, for clusters selected in the X-ray with the XMM-LSS ($kT > 2$ keV and $S_{[0.5-2.0\ \mathrm{keV}]} > 8 \times 10^{-15}\ \mathrm{erg\,cm^{-2}\,s^{-1}}$). The X-ray cluster counts are shown both for a ΛCDM model (with $w = -1$) and for a QCDM model ($w = -0.8$). We also show the predicted cluster counts expected from the weak lensing analysis (Bartelmann et al, 2002)

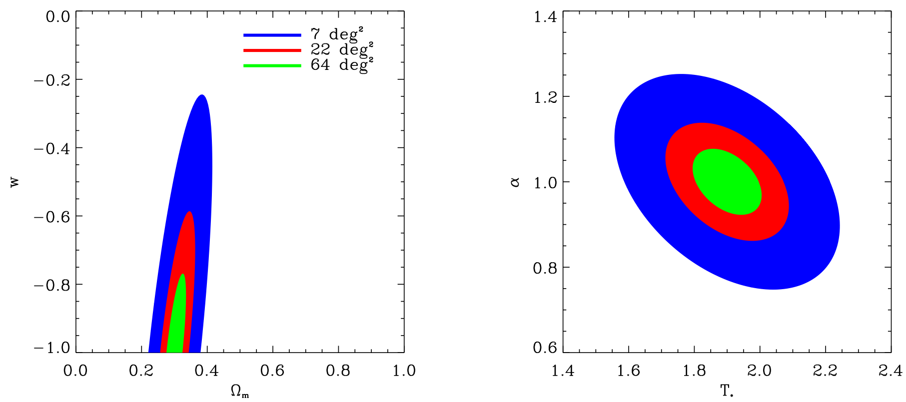

Figure 2. <u>Left:</u> Constraints on cosmological parameters at various stage of XMM-LSS coverage. Priors for σ_8 from WMAP and mean cluster scaling relations were assumed. <u>Right:</u> An example of constraints on the cluster scaling relations from the survey. The cosmological parameters Ω_m and H_0 were fixed to the WMAP values. The prior from WMAP for the σ_8 was assumed (a preliminary figure from Refregier et al, 2004).

ary trends of the scaling relations and, subsequently, characterize the impact of the many processes presented in Sec. 1 & 2 on cluster physics and observables. Both aspects of such an approach are illustrated on Fig. 2 for different stages of the survey coverage. The XMM-LSS survey could improve on WMAP's measurement of Ω_m and constrain the dark energy equation of state parameter w, to which WMAP is not sensitive (Fig. 2, left). Alternatively, assuming that the cosmological parameters are well constrained (by a combination of WMAP, supernovae observations and nearby very large scale galaxy surveys), the evolution of the cluster scaling laws can be followed (Fig. 2 right). The parameters T_* and α describe the amplitude and evolution of the mass-temperature relation ($M \propto T^{3/2}$ for $T > 2$ keV). The XMM-LSS has the potential of determining T_* and resolving the controversy of its value, which has been given as low as 1.2 or as high as 1.9 (see Pierpaoli et al, 2003). The survey is also able to constrain the evolution parameter, α, which has been fixed to 1 in earlier work. This is possible with the XMM-LSS survey because of the large cluster sample and wide range of redshifts.
At a later stage, observations from associated Sunayev-Zel'dovich and weak lensing surveys will yield further constraints on the scaling relation of clusters, and will impose *simultaneous* constraints on cosmological parameters and cluster physics.

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